New High-Definition Microelectrical Images Shed Light on Complex Paleozoic Nubian Sandstone Reservoir*

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Abstract

The Ras Budran oilfield, operated by Suez Oil Com-pany, was first discovered in 1978 and lies approximately 2.5 mi (4 km) off the Sinai coast of the Gulf of Suez. Oil is produced from three units of Nubian Formation sandstone from a depth of 11,000-12,000 ft (3,352-3,657 m). The lower unit, of Paleozoic age, averages 10% porosity and has up to 200 md in-situ permeability. However, multiple sedimentary and diagenetic facies present within the unit result in large variations in porosity and permeability at both wellbore and reservoir scale, and make it unreasonable to consider the unit as a single hydraulic zone. Unfortunately, it is impossible to recognize these facies from the evaluation of standard petrophysical logs, which have been the norm in Ras Budran until recently.

To shed new light on the problem, a new high-definition microelectrical imaging tool was logged in RB-B13 and yielded the first-ever high-resolution images of Nubian Sand, despite the well having been drilled with non-conductive oil-base mud (OBM). While microelectrical imaging technology adapted for the OBM environment has been available for the last decade, the spatial resolution, coverage, and sensitivity to formation texture offered by these devices is not sufficient for detailed evaluation of structural, sedimentary, and diagenetic features present in the field. The new high-definition imager is based on the physical design of the industry-standard imager for conductive water-base mud (WBM) and thus features the same high spatial resolution and coverage. New electronics featuring improved signal processing and a higher signal-to-noise ratio extend the use of the new tool to the OBM environment under specific, favorable conditions that are present in Ras Budran.

Based on formation sedimentary and diagenetic features clearly observed in the high-resolution images, ten facies were clearly identified and classified over the entire sand unit, resulting in accurate flow unit delineation. Further studies presently aim to link facies to porosity-permeability relationships. In addition, multiple fracture sets were identified and interpreted as mineral-filled, implying influence as permeability baffles.

Interpretation of high-resolution formation images has allowed the operator to establish an understanding of this Nubian Sand reservoir's complexity in terms of fracturing and diagenesis. The insight gained positively impacts the operator's completion and enhanced oil recovery strategy.

Imaging in Oil Base Muds

As nonconductive oil-base drilling fluids gained popularity, many researches took place to understand better the behavior of electrical current in non-conductive muds. Early 2001, OBMI (Oil Base Micro Imager) was introduced to the market, and it represented the first imaging tool that provides high resolution images in oil base muds. It generates the image by passing electrical current into the formation from two large electrodes on each pad, which is at a very high voltage (about 300V). There is a series of closely spaced buttons, located in two rows of five on each of the four pads.

Conventional microelectrical imaging tools were designed with the assumption that the mud was electrically much more conductive than the formation; many operators experimented with running the FMI tool in oil-base mud, but were disappointed with images that were dominated by noise with very few geologic features visible. That is why it was crucial to understand the novel signal processing.

High Definition Imaging

The new high-definition micro imagers deliver more detailed and higher images than the original industry-standard formation micro imager. The tool is redesigned from inside with new hardware full replacement but within the same field proven micro imager sonde (Figure 1). The enhanced analog-to-digital circuits and parallel signal processing improved the signal-noise ratio, giving more reliability in extreme conditions and mud properties. Fair high-resolution images can be obtained from high definition micro imager in non-conductive mud, with specific mud conditions.

Nubian Sand

Nubian Sandstone refers to a variety of sedimentary rocks deposited on the Precambrian Basement in the eastern Sahara, northeast Africa and Arabia. It consists of continental sandstones with thin beds of marine limestones, and marls. Nubian sandstone was deposited between the Lower Paleozoic and Upper Cretaceous, with marine beds dating from the Carboniferous to Lower Cretaceous. The Nubian sandstone complex has a thickness varying from under 500 m to over 3,000 m, resting on the Precambrian basement. This is complicated by various structural faults and fold axes traversing the region in a northeasterly direction.

Ras Budran Field

Deminex (as operator for its partners, British Petroleum and Shell) discovered Ras Budran oil field in 1978. Discovery well EE 85-1 was drilled in approximately 140 ft (42 m) of water, 2.5 mi (4 km) off the Sinai coast of the Gulf of Suez. Ras Budran field now is operated by SUCO and the oil is produced from three units of Nubian Formation sandstone from a depth of 11,000-12,000 ft (3,352-3,657 m). The lower unit of Paleozoic age averages 10% porosity and has up to 200 md in-situ permeability.

FMI-HD was logged in RB-B13 well as the first micro-imager to be logged in Nubian Sand in non-conductive mud environment. Nubian Sand needs to be clearly evaluated in terms of primary structures and diagenetic effects, which made it difficult to be seen with conventional oil based mud imagers. Nubian Sand was proven to have multi facies, which made it impossible to average the full reservoir into one zone. The high definition micro-electrical images acquired have greatly enhanced the clients' understanding of the facies distribution throughout the Nubian Sand.

A resolution of five mm would give the chance of recognizing deep image texture as a reflection of the internal sand texture, hence permitting an adequate facies and texture extraction. In addition to the image, calibration that is performed with the help of some other available data like conventional core and thin sections.

Nubian Sandstone Facies Analysis

Following acquisition of the image, a structural interpretation and facies analysis were carried out on the Nubian Sandstone to determine paleocurrent direction and facies distribution respectively. Six different types of sandstone facies were derived from the detailed facies analysis over the Nubian Sandstone, leading to better reservoir delineation and better reservoir treatment in terms of enhanced oil recovery.
These six types of Nubian sandstone facies are categorized as follow:

- Cross bedded sandstone
- Laminated Sandstone
- Massive Sandstone
- Kaolinitic Sandstone
- Hematitic sandstone
- Fractured Sandstone

These facies were identified based on the detailed analysis of the internal Sandstone texture using the high definition micro-electrical image with the integration of the thin sections as well.

The following figures summarize the above-mentioned facies obtained from the high definition micro-electrical images. The first figure shows coarse-grained massive sand filled with ferruginous cement (Figure 2). Ferruginous cement appears conductive on the image but destroys the reservoir's porosity and permeability. Fe^{2+} is dissolved from ferromagnesian minerals during diagenesis is oxidized to Fe^{3+} and precipitated as ferruginous cement. The first figure also shows coarse-grained massive sand in a conductive background interpreted as kaolinite (Figure 2). Nubian Sandstones are typically comprised of quartz arenties and wackes. Diagenesis results in the alteration of feldspars to clays, mainly kaolinite (Alsharhan and Salah, 1997). As a layered silicate clay mineral, kaolinite can occur as a diagenetic pore-filling mineral or as an authigenic layered clay. Both types are encountered in well RB-B13 where patches of kaolinite are observed if they are diagenetic pore-filling clays and layered if authigenic clays coating the quartz grains. In most cases, kaolinite acts as a vertical permeability baffle within the sandstone or fills up porosity as digenetic clay. The third figure shows one of the many heavily fractured and faulted sand units throughout the

Nubian Sandstone (Figure 3). The fractures appear conductive on the image, indicating that they must have been cemented with conductive clays since the well was drilled with oil-based mud. In the case of water based mud the other possibility would have been that the fractures are open but invaded with the water based mud; giving them a conductive appearance. A relationship is observed between the fractures and the faults they surround; the general fault strike direction in the Nubian Sand is NW-SE, which is the same strike orientation of the associated fractures. This suggests that the same deformation episode acted on Nubian Sand and resulted in the generation of these faults and fractures that are created during the Oligo-Miocene rift parallel to the Clysmic trend prevalent in the Gulf of Suez. The fourth figure is of a cross-bedded sandstone unit that is repeated throughout the Nubian Sand (Figure 4). Cross-bedded sands are also a good indication of paleocurrent flow direction following structural dip removal, which would in turn enhance future well delineation

The facies analysis generated was integrated with the combinable magnetic resonance and ELAN analysis (Figure 5). The calibration to the microscopic thin sections was also performed for getting a reliable and representative electrical facies (Figure 6). Suez Oil Company now has a better understanding of their reservoir complexity in terms of fracturing and diagenesis, which is the most complex task when studying Nubian Sands.

Conclusions

The new high definition imager give the possibility of getting the same image resolution and same well proven image contrast in non-conductive muds but with specific mud parameters. The RB-B13 well was drilled in the Nubian Sandstone (Paleozoic Sand) and for the first time the full Nubian Sandstone was imaged for SUCO. Detailed image interpretation showed how the internal texture of the Nubian Sand was heavily affected by the diagenetic process that has undergone this old sand. Facies are not only controlled by the depositional aspects, which made it complicated to evaluate the strange flow behaviors encountered within the Nubian Sand. Image interpretation revealed a multi facies scheme seen in the sandstone. It was crucial to understand how these facies would control the major flow units and helping with the reservoir development.

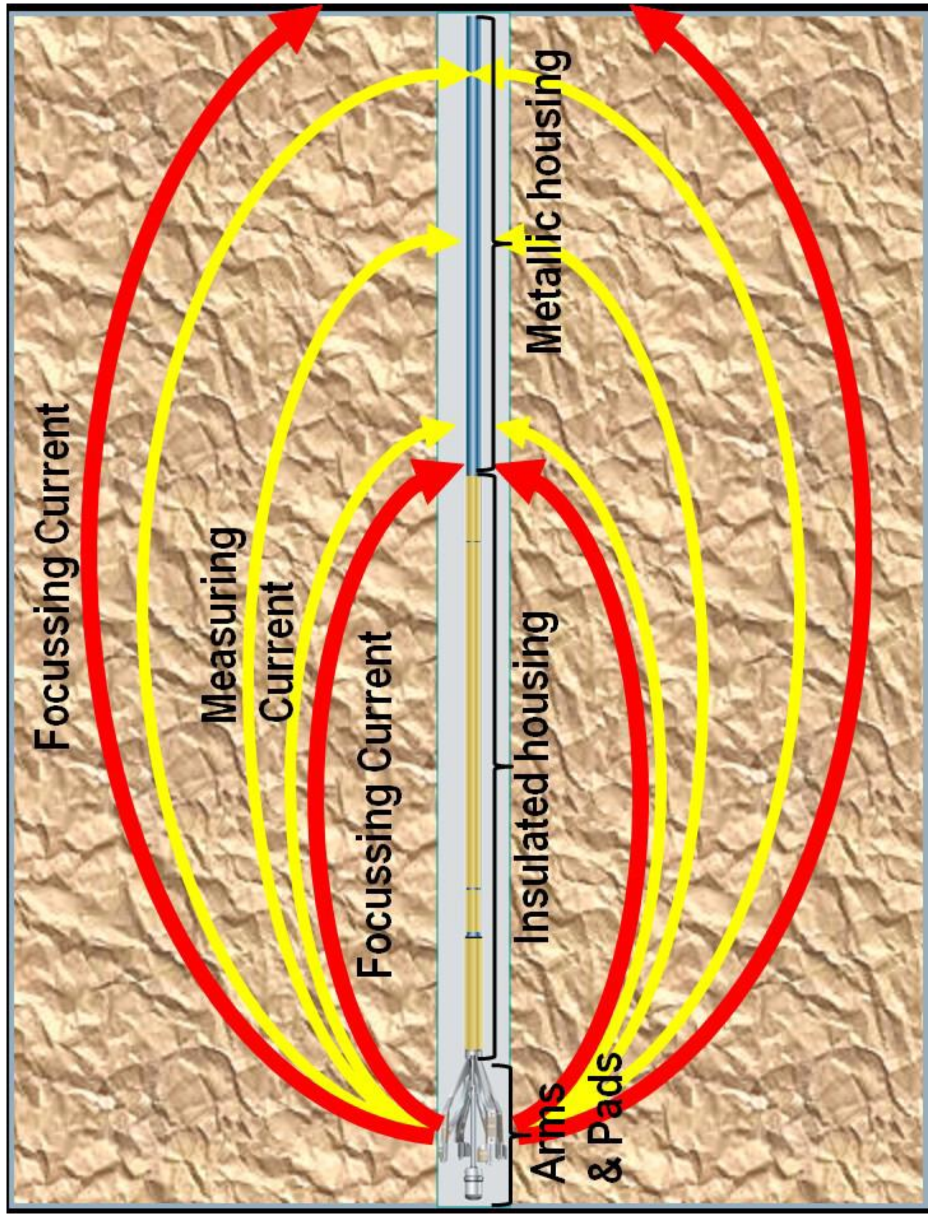

Figure 1. Physical arrangement and current flow path of formation micro imager tool.

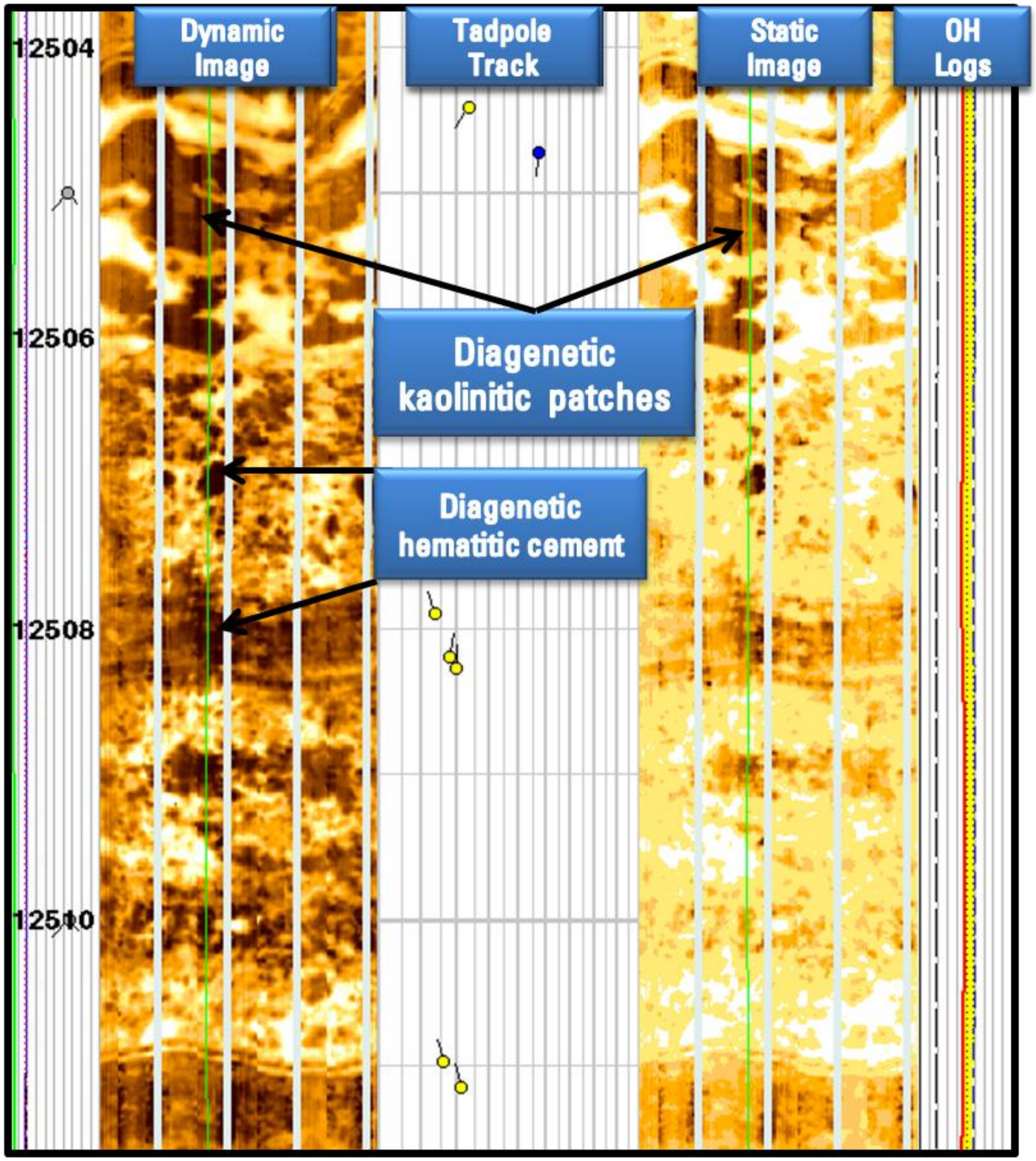

Figure 2. Coarse-grained sand with what is interpreted to be conductive ferruginous cement in between the grains (12,510-12,506 ft). The coarse grains can also be seen in a conductive background, which could be interpreted as kaolinite patches (12,506-12,504 ft). Both the kaolinite patches and ferruginous cement would affect the reservoir quality by plugging up porosity and permeability pathways. Scale 1/10.

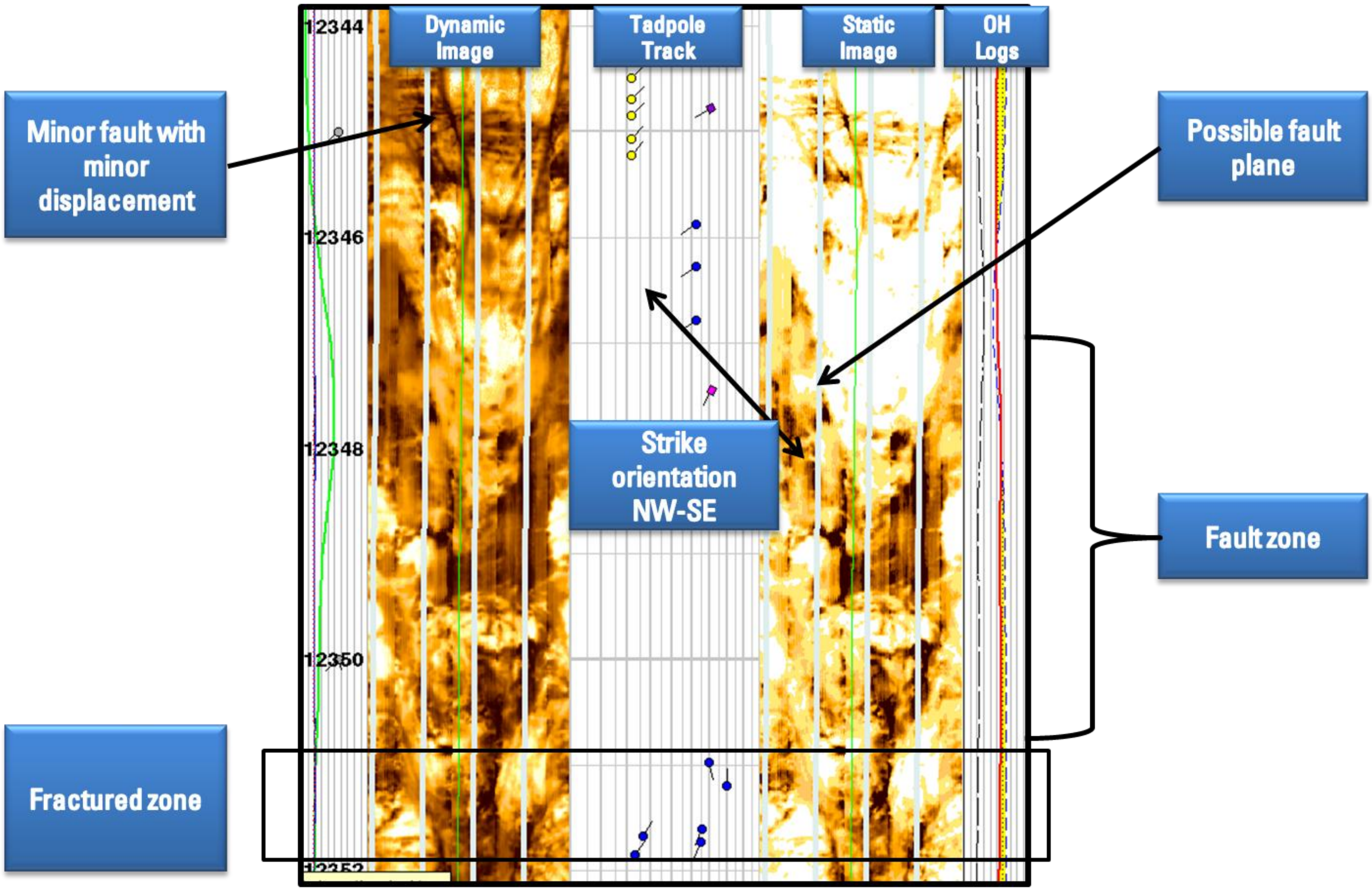

Figure 3. Possible fault plane at 12,347 ft in sand striking NW-SE with associated fractures above and below as well as a fault zone separating a conductive section from a more resistive one. The fractures are cemented with conductive clays, which can be interpreted due to the use of oil-based mud. The fault strike is aligned with the Clysmic trend ob-served in the GOS region. A minor fault is also visible with displaced beds at depth 12,345 ft. Scale 1/10.

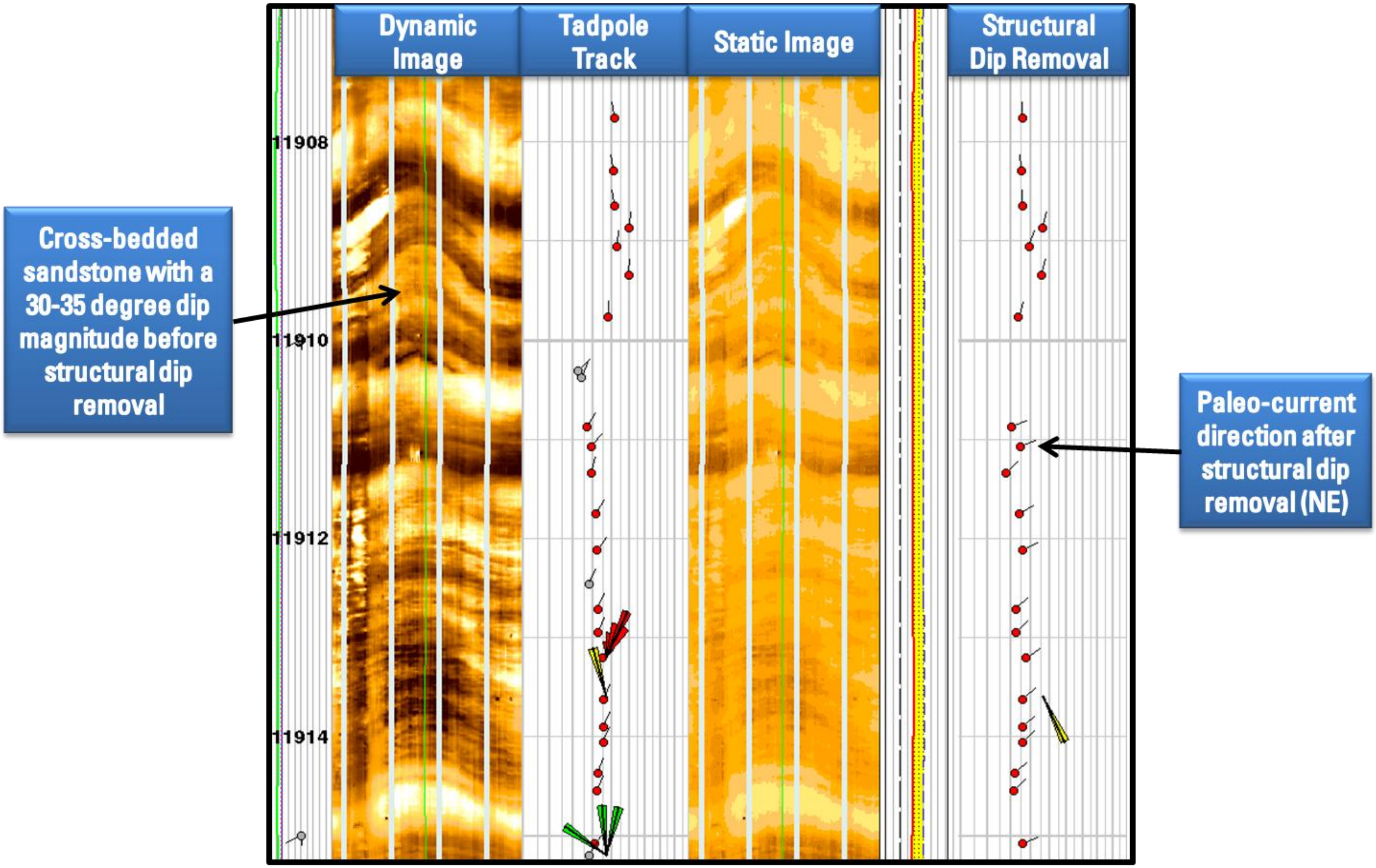

Figure 4. Cross-bedded sand (11,914-11,908 ft) in red oriented NNE and dipping 35 degrees before structural dip removal (left). After removal (right) the azimuth shifts to the NE while the dip magnitude drops to 25 degrees. Co-set boundaries in grey are oriented NE and dipping around 20 degrees (less than cross-beds). Cross bedding is due to deposition under a high-energy flow regime while the co-sets represent a change in the hydrodynamic properties of the flow regime. Scale 1/10.

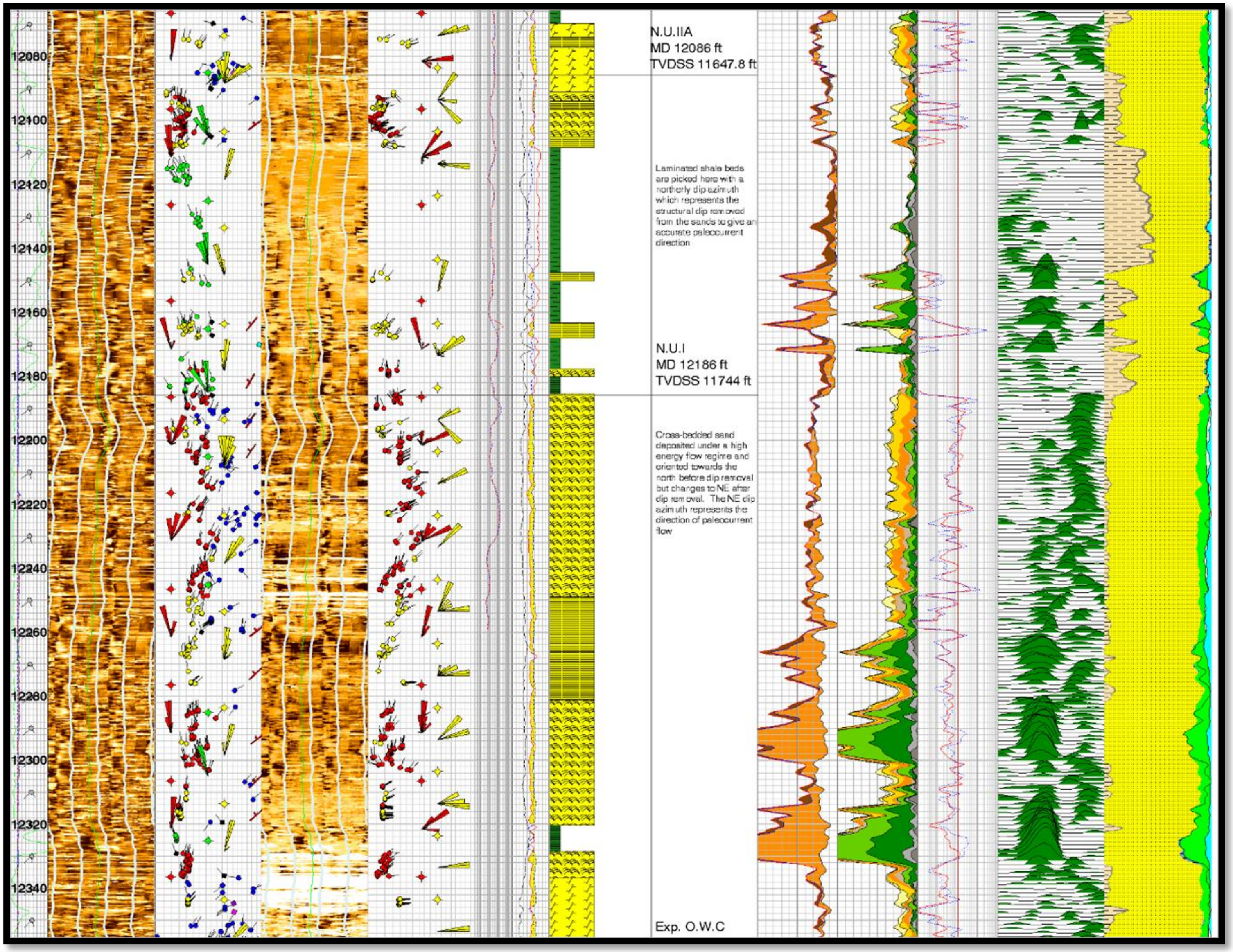

Figure 5. A 1/200 scale view of the lower Nubain Sandstone showing cross-bedding fractured zones, laminated sands and shale. The lowermost part of the snapshot is showing an example of the fractured and cross-bedded sandstone. The paleocurrent analysis performed over the Nubian Sandstone in Ras Budran field revealed the presence of flow direction carrying the sand sediments from SW toward NE direction. The integration results of the facies generated from the new definition high resolution electrical image, ELAN and combinable magnetic results showed the best hydrocarbon bearing zones as flagged by the black boxes on the figure.

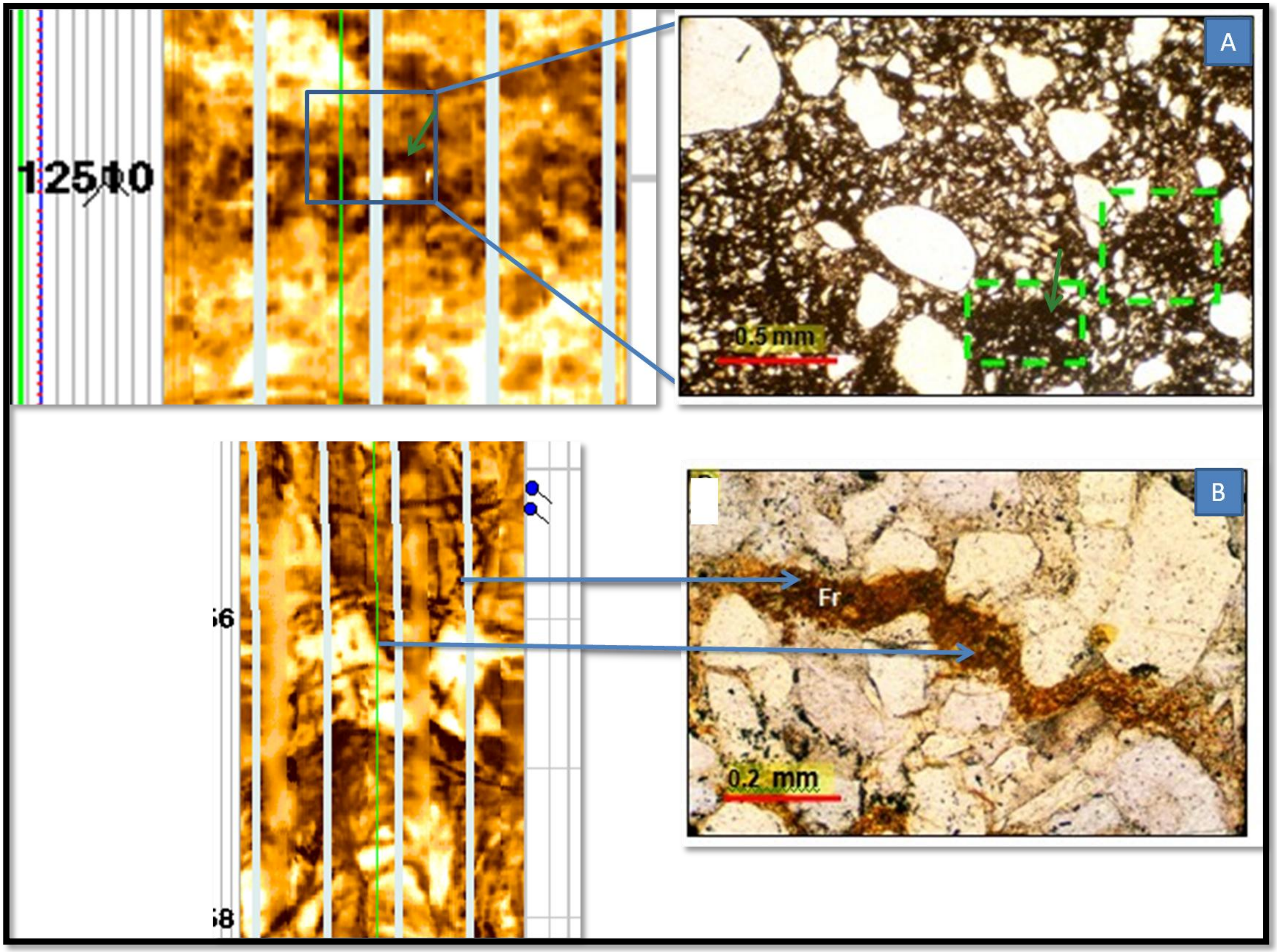

Figure 6. A) Image to thin section calibration showing the diagentic clays filling the pore spaces of the Sandstone. The green arrows refers to the hematitic cement; B) Image to thin section calibration showing example of the hematitic filled fracture which appear darker or conductive on the electrical image.